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An error-correcting system for a multi-channel digital sound recorder

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AN ERROR-CORRECTING SYSTEM FOR A MULTI-CHANNEL DIGITAL SOUND RECORDER

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Summary

This report traces the development of a single track per channel error-correcting scheme for a digital sound recorder.

The use of data re-ordering as a technique for turning burst errors into single bit errors is discussed, and the performance is shown to be inadequate, when associated with sample repetition for concealment.

Error correcting codes are dealt with, using cyclic redundancy code (CRC) checking both in a correcting and detecting mode, as is a 2,1 Wyner-Ash convolutional code, all of which use four tracks per channel and can cope with total loss of one of these tracks.

The development of a single track per channel system from a three track per channel system using a CRC is outlined, and the parameters of a recorder using this scheme are given. The length of drop-out that can be withstood on the single track is longer than any likely to be encountered.

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1. Introduction

For the past three years, the 3M Company and the BBC have been engaged in a co-operative venture to design a multi-channel digital sound recorder, with very low distortion and noise levels, which it is hoped will be attractive to the recording and broadcasting industries. An essential part of such a recorder is an error detection and correction scheme, which will deal effectively with the inevitable errors in the replayed signal, caused by tape drop-outs. The joint research programme has centred mainly on the nature of the correcting scheme to be employed. Several suitable methods were devised and tried, and the chosen one is considered to be the best compromise between the demands of correction efficiency, economical tape consumption and the ability to accommodate the highest possible number of sound channels.

2. Error concealment using re-ordering of data

The main factor influencing the choice of an error-correcting scheme for a magnetic tape recorder is the nature of tape drop-outs. They tend to be of such a size that each dropout can affect many hundreds of bits. There are concealment systems[1] which involve the detection of digital words (samples) in error by simple parity checking and the concealment of errors by the replacement of faulty words with the most recent good word, or by simple interpolation. These methods have been used successfully in digital transmission systems and in an early digital stereo recorder built by the BBC,[2] but they are not really suitable for a multi-channel recorder. However it is possible to re-order the data as it is put on to the tape, and to restore the original order on replay in such a way that bursts of errors due to drop-outs result in spaced single-bit errors in the replayed bit stream. Only single words will therefore be in error, and a concealment system of repeating good words would be a possible means of dealing with these errors, as shown in simplified form in Fig. 1.

Two forms of re-ordering were simulated; firstly a pseudo-random type, in which a burst of errors becomes a series of randomly spaced single errors, and secondly a system whereby a burst error is transformed into a longer block containing regularly spaced single errors. Concealment by repetition is then applied.

Neither of these re-ordering systems reduced the noise due to drop-outs to an acceptable level, though both reduced the disturbance considerably.

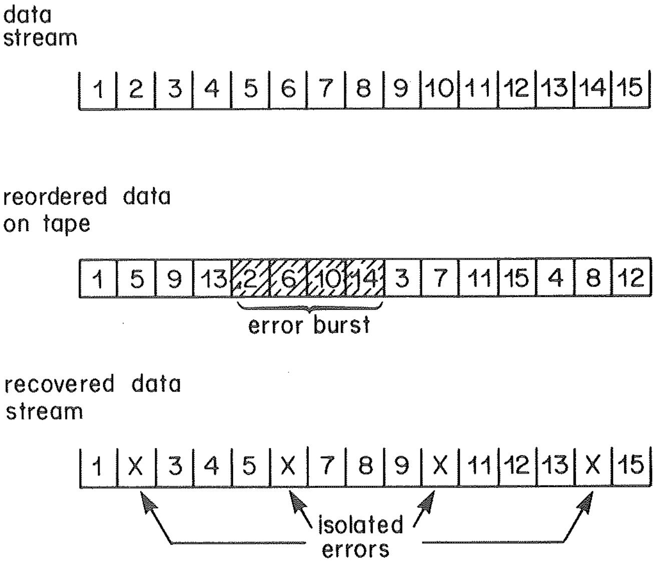

Fig. 1 - Re-ordering for error correction

3. Error correction fundamentals

The words 'channel' and 'track' are often used interchangeably. In most cases this is completely justified and little or no confusion results. However, with the introduction of digital sound recorders, there is an almost limitless variety of possible recording formats, many of which require a clear distinction between sound channels and tape tracks. Using digital techniques for example, it becomes a very simple task to divide the digital sound channel into two, and record it on two tape tracks with an appropriately lower tape speed. It will be increasingly important to consider digital sound recorders in terms of the number of tracks per channel, as that number markedly affects cost, editing, and error correction capability.

In turning attention to means of error correction (rather than concealment), it was expected that more than one track of a recorder would be allocated to each sound channel. With a reasonable track width (about 0·5 mm (0·020 inch)), it is rare for a tape drop-out to affect more than one track at a time. It was decided therefore to aim for a correcting system that would completely correct drop-outs of any duration provided that only one track associated with any one channel was affected at a time.

If the data from each sound channel is distributed between several tracks, this then means that if there are, say, b bits from each word on each track, it must be possible to correct burst errors of length b in any word. In general, to be completely sure of correcting such errors, it is necessary to use $2b$ parity bits per word.[4] If, therefore, many tracks are allocated to each channel (and b is consequently small), few parity bits are needed. Conversely, if b is large (few tracks per channel) many parity bits per word are required. Further, the fewer tracks are used per channel, the more sound channels may be provided on a given tape width.

For a digital system which employs 13 bits per sample word, a reasonable compromise seemed to be to use two information tracks per channel, with seven bits from each word on one track and six plus a dummy bit on another. (The dummy bit could be used to accommodate 14 bit coding.) Therefore for complete correction, two more tracks are necessary each with seven parity bits per word. This may seem at first sight to be very extravagant, but in practice, considering the extreme severity of the effect of large drop-outs, it seemed a reasonable price to pay for efficient error correction. In a practical system, the bits would not necessarily be arranged exactly as described here.

4. Four tracks per channel with cyclic redundancy check

In the first error-correcting scheme, the parity bits were the remainder resulting from a division of each 13-bit data word by a cyclic block-code generator polynomial[5] of order 15, leaving a remainder of order 14. This in fact means that there would be 15 parity bits added to 13 data bits making 28 in all (seven on each of four tracks). Thus a continuous drop-out on one track would result in a maximum of seven errors in each word, which a code such as that described can correct.

Fig. 2 shows the way in which a serial stream of data and remainder bits is distributed among four tracks.

This system, often described as a 'cyclic redundancy-check (CRC)', is however very complicated indeed to instrument, as commercially available polynomial generators do not have the facility for decoding the remainder for error-correction purposes where it is non-zero, and so they can only be used for error detection. The required logic to yield error-correction has therefore to be built up from individual shift registers.

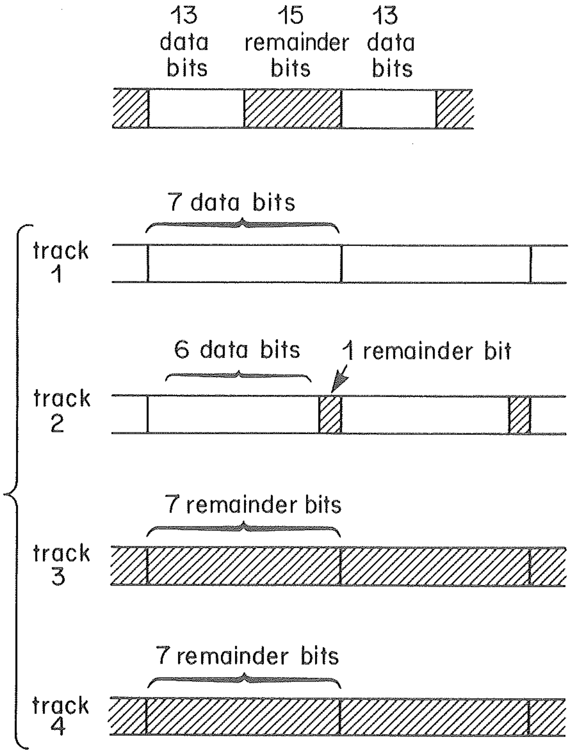

Fig. 2 - Cyclic redundancy code (CRC) format used for correction

5. Four tracks per channel with Wyner-Ash code

The complication needed to instrument the previous system led to a search for an alternative, which, it was hoped, would have the same error-correction capability but would be much simpler to implement.

Such a system was devised by the use of a (2,1) Wyner-Ash convolutional code[6] which is capable of correcting a single bit-error in any group of four bits, provided at least three good bits appear between errors. The arrangement is illustrated in Fig. 3. Parity (P_n) is formed from each pair of adjacent data bits (D_n and D_{n+1}), each data bit being therefore associated with two parity bits. These are then arranged across the four tracks as shown, and it will be noticed that failure of any one track results in only one bit in error in a group of four, with three good bits between errors. Single track failure is thus correctable.

Figs. 4 and 5 show the parity failure pattern caused by errors in a data track or a parity track. The former always cause parity failures involving an even number of parity bits and, by examining the parity bits in pairs from the start of the error, the data bit which is wrong can be detected and put right. Errors in a parity track, however, involve only single parity-bits and no action need be taken.

This correction scheme was the one finally adopted in the 10 channel experimental machine built in Research Department,[7] now in regular use whenever a high-quality sound recording is needed.

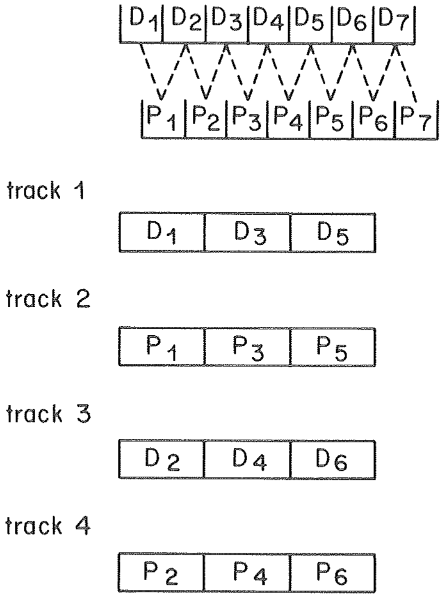

Fig. 3 - Format for 2,1 Wyner-Ash code

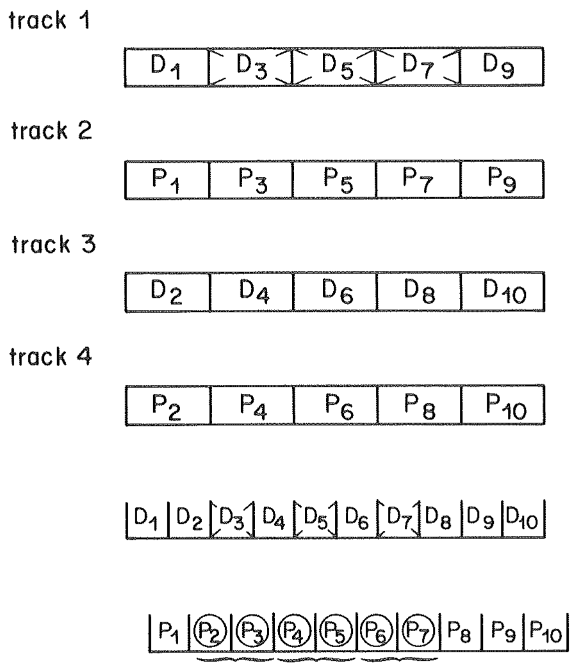

Fig. 4 - 2,1 Wyner-Ash code: parity failure pattern for information track errors

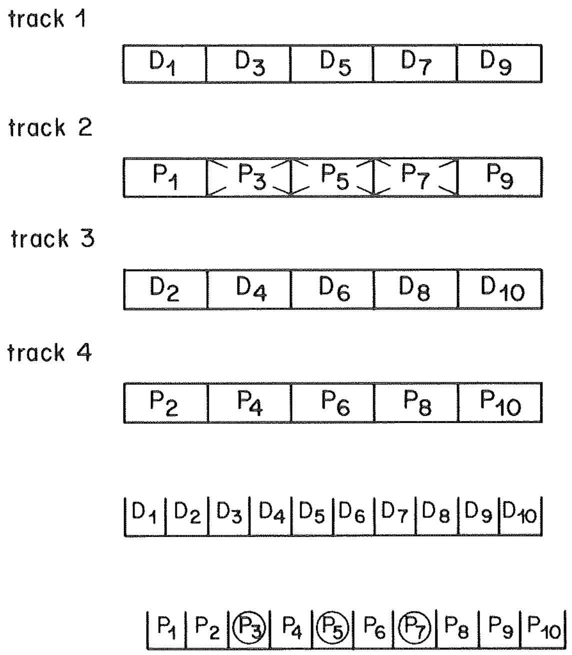

Fig. 5 - 2,1 Wyner-Ash code: parity failure pattern for parity track errors

6. One track per channel with cyclic redundancy-check

For economic as well as editing reasons it is highly desirable to use as few tape tracks per audio channel as possible, preferably one track per channel. If many tape tracks per audio channel are to be used, the complexity, and therefore the cost of the record and replay heads increases rapidly if the recorder is to be a 24 or 32 channel machine.

The error correction system to be described for one track per channel[8,9,10] can best be understood as a modification of a three track per channel system as follows:

One audio channel is recorded on two tape tracks in some convenient manner by demultiplexing, permitting a halving of the tape speed that would otherwise be required. Attached to a specified number of bits are cyclic redundancy check digits. Thus a high proportion (≏99·8%) of all errors in this specified block may be detected. The third tape track is a block of information made up of simple even or odd parity checks 'across' the two audio tracks. This parity track is generated bit by bit for the full length of the audio block, and it has its own set of CRC check digits. As an example (see Figure 6) parity bit P_1 is generated from an even or odd sum of D_1 and D_2.

Making the assumption that errors will affect only one track at a time, errors can be corrected by using the CRC to indicate the track that has been affected by the drop-out, and the parity bits to reconstruct the incorrect data. If a drop-out does affect more than one of the three tape tracks within the block at the same time, insufficient information is available to perform error correction and the system must then rely on error concealment.

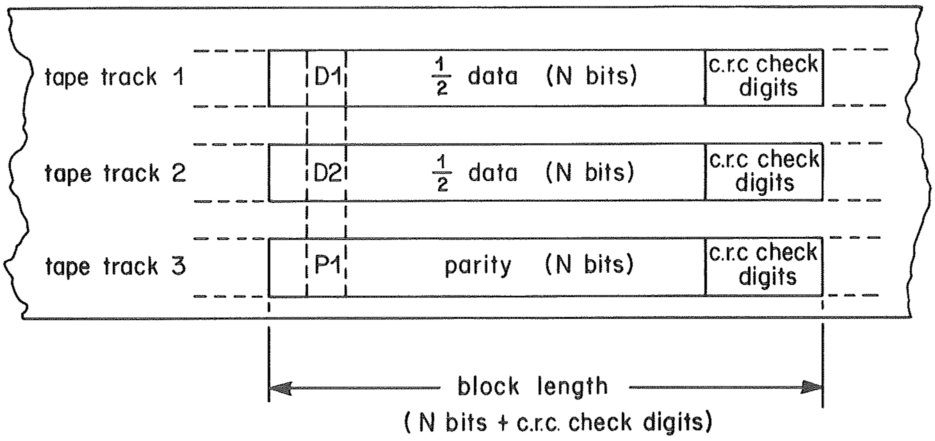

Fig. 6 - 3-Track per channel error-correction format using CRC

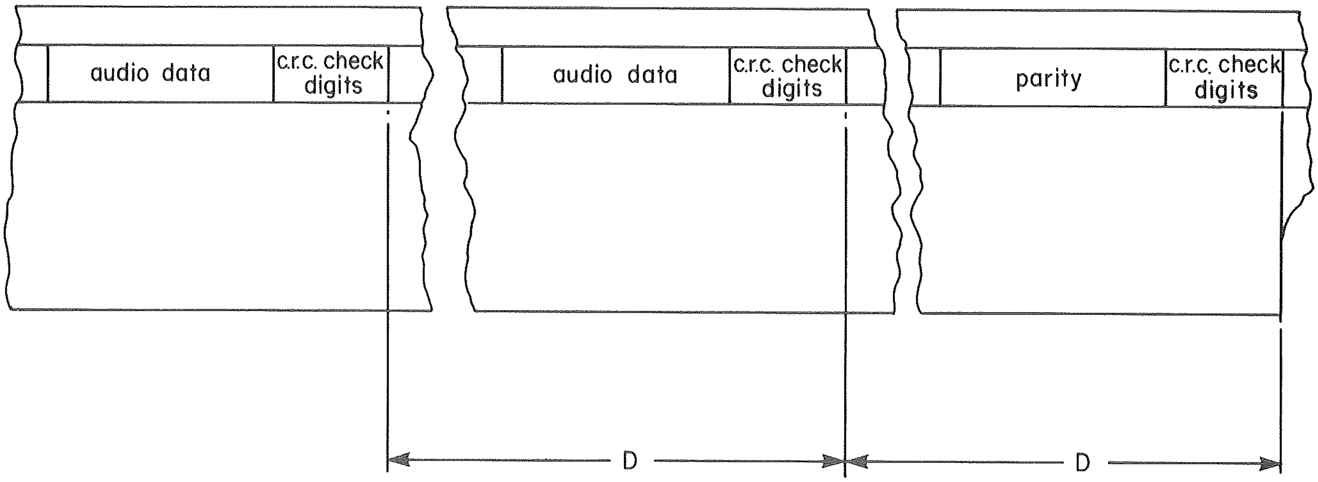

Fig. 7 - Single track per channel error-correction format using CRC derived from 3-track per channel scheme

Instead of recording the three blocks of data (two audio and one parity) on three separate tracks, it may all be recorded on a single tape track. The three blocks however are not recorded next to each other along that track, but are delayed with respect to each other and recorded separated by distance D (Fig. 7).

All the audio data blocks and the associated parity blocks are recorded in this manner so as to produce a continuous data stream. As with the three track system, drop-outs, if they are to be corrected, must affect only one of the three interrelated blocks. However, drop-outs much longer than one block length (up to distance D) are correctable as they affect no more than one block in each set of three related blocks. Once the drop-out has exceeded the critical distance D, there are uncorrectable errors which must be dealt with by some suitable error concealment method. Distance D is chosen having regard to the maximum length of drop-out that is anticipated, and by the cost of the digital storage needed in the record and replay circuits.

During recording, two of the blocks must be delayed with respect to the other (one by D and the other by $2D$) so as to provide the spatial separation on tape. When reproduced, these blocks must again be delayed in order to check the parity block against the two data blocks and reconstruct the data if there have been errors.

The system as described will require a higher tape speed than the same system without error correcting capabilities. In fact assuming a constant bit-density on tape, the tape speed will be 1·5 times that of a system without error correction. Other less redundant systems can easily be devised where there are perhaps 3 or 4 (any number is possible) audio blocks for each parity block, with a corresponding tape speed of 1·33 or 1·25 times that of the system without error correction. The disadvantage of these systems, with a relatively large number of total blocks, is that errors, if they are to be correctable, may still occur in only one block at a time.

The extreme case with a minimum number of blocks produces one parity block for each data block. This is a 100% redundant system where the parity bits may as well be replaced by a repeated data block. The major disadvantage is that the tape speed is doubled.

On the basis of the considerations described above, experimental recordings were made by the 3M Company and BBC Research Department* which showed that the following choice of parameter values should give a satisfactory compromise between tape speed and error correcting capability, with a bit packing density of about 1100 bit/mm (28 kbit/inch).

Tape speed	1·14 m/s (45 inch/s)
Data blocks per parity block	2
Length of block	400 bits
CRC word length	12 bits
Spacing between blocks (D)	15 blocks (400 bits each) = 6000 bits
Protected drop-out length	5 mm (0·2 inch)

7. Conclusions

An error correcting scheme, based on a cyclic redundancy code and simple parity checking, has been described which is being used in the development of a multi-channel digital sound recorder with 32 sound channels,[11] using 25·4 mm (1 inch) tape running at 1·14 m/s (45 inches/sec). This gives up to 45 minutes playing time with a suitable tape and reel size. The performance of such a machine (in terms of signal/noise ratio, wow and flutter, and distortion) will be superior to that of current analogue machines using conventional noise-reduction systems.

8. Acknowledgement

Thanks are due to Marshall R. Brookhart (formerly of the 3M Company) for many helpful discussions, and for the

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* The BBC equipment was built and tested by M.K.E. Smith.

building and independent testing of some of the systems described.

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